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Investigations of Variability for Ship Navigation through the Northwest Passage, 1982-2010

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ABSTRACT
Considerable effort has been given to developing systematic methods for evaluating the safety of ship passages through ice-infested Canadian Arctic waterways (Timco *et al.,* 2009). Recent analyses (Fissel *et al*, 2010; Mudge *et al.,* 2010) of Canadian Ice Service weekly ice chart data (1982-2010) have utilized the resulting Transport Canada's AIRSS navigability system to quantitatively assess interannual trends and geographical details associated with the traditionally difficult to navigate Viscount Melville Sound, M'Clure Strait and Prince of Wales Strait portions of the Northwest Passage (NWP) Routes. The present work extends the Fissel *et al*. (2010), and Mudge *et al*. (2010) full navigation season analyses to assess value, feasibility and methods for incorporating shorter time scale (daily) ice and other environmental information into ship transit navigation models. Analysis products are compared with Canadian Coast Guard icebreaker passages through the NWP from the period 2003-2010 to appraise effectiveness and promising directions for model improvement. The NWP is used to develop geographically transferrable methods of using environmental data for now-time analyzing the navigability of ice conditions. Emphasis is given to establishing stand-alone procedures and tools for the near-daily time scales of Polar and sub-Polar marine traffic management.

KEY WORDS: Northwest Passage; shipping; sea ice; trends; climate change.

INTRODUCTION
Continued analysis has been carried out on the impact of sea-ice on shipping in the deep water route of the Northwest Passage (NWP). The Northwest Passage (Figure 1) is the shipping route between the Atlantic Ocean (Baffin Bay) to the Pacific Ocean (Bering Sea). There are three potential routes, a shallow and well used route through Peel Sound, a deep water route through M'Clure Strait (MS) and a second, and generally preferred, deep water route through Prince of Wales Strait (POWS).

Historically, high concentrations of deformed thick first-year ice (FYI) and multiyear ice (MYI) are present at choke points in MS, Viscount Melville Sound (VMS) and northern POWS even during the summer and fall months when total sea-ice coverage reaches a minimum (Figure 1; Falkingham *et al.,* 2003). The shallow route is often blocked at a third chokepoint in the Victoria Strait, north of Queen Maude Gulf. These blockages in VMS and POWS have reduced or eliminated the use of these routes apart from the exceptional year. Conditions in MS are typically even more severe; thus, we have focused our analysis on the preferred VMS/POWS routing.

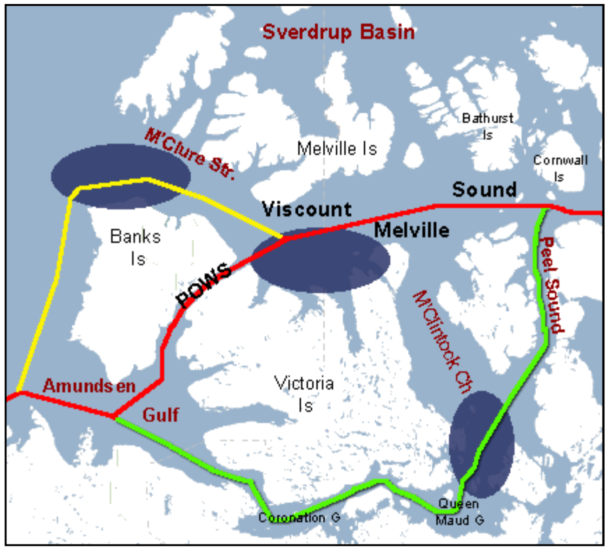
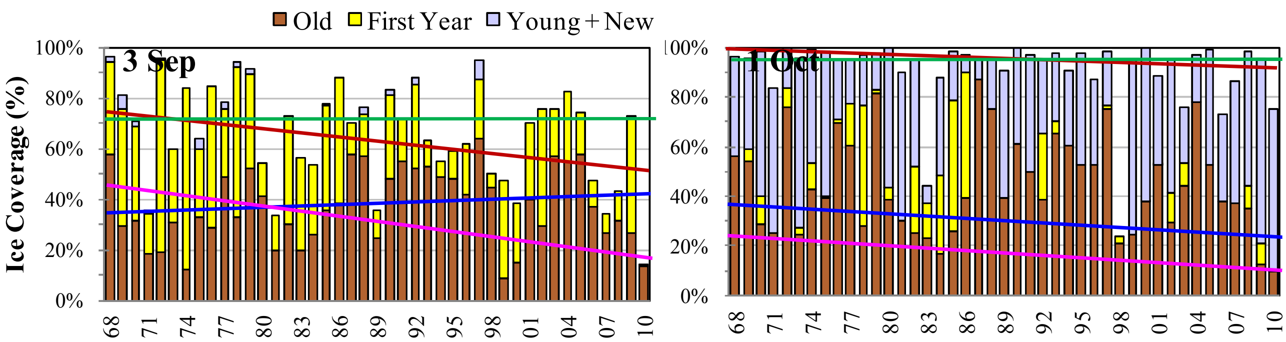


Figure 1. NWP deep route in red, shallow in green, and the least travelled in yellow; navigation choke points (from Wilson *et al.,* 2004) are shown in blue.

ICE CONDITIONS

Tivy *et. al.* (2011) have shown that the 1968 to 2008 record of total sea-ice coverage in the Canadian Arctic Archipelago follows similar trends as the reduced sea-ice coverage of the entire Arctic Ocean (-11.5% per decade NOAA, 2011). The long-term trend from 1968 to 2010 in the VMS (Figure 2) is also towards lower sea-ice coverage, but the 5.8% per decade trend is smaller than that observed for the Arctic Ocean and is also smaller than the inter-annual variability. While the total sea-ice coverage has reduced, the more hazardous to shipping MYI coverage has had the opposite trend in early September of 1.5% per decade. Tivy *et. al.* (2011) noted similar trends of increased MYI in VMS of the Western Parry Channel and all regions of the Eastern Parry Channel.

The reduction in total sea-ice in VMS is consistent with the increased melting of FYI. It is suspected that this increased melting has weakened blockages that traditionally bar the movement of MYI from the Sverdrup Basin of the Queen Elizabeth Islands (QEI) and from Beaufort Sea entering VMS (Melling, 2002). As the blockages in both the QEI northern channels to the Arctic Ocean, and in the southern channels (Byam, Austin, Crozier, and Wellington Channels) have weakened, the predominately westerly winds have driven MYI generated in the Beaufort Seas and Sverdrup Basin into MS and VMS. The weakening blockages produce a more complex dependence of ice conditions in VMS on inter-annual variability, such as the Arctic Oscillation, El Nino Southern Oscillation and long-term global warming.



	3 Sep	1 Oct
Total Ice Median:	70.5%	95.5%
Total Ice Trend:	-0.58% Slope, 20.1% StDev	-0.23% Slope, 14.5% StDev
Multiyear ice Trend:	0.15% Slope, 14.9% StDev	-0.2% Slope, 20.0% StDev
First Year Ice Trend:	-0.68% Slope, 17.9% StDev	-0.22% Slope, 14.1% StDev

Figure 2. Sea ice trends for September 3 (*left*) and Oct 1 (*right*), 1968-2010 for Viscount Melville Sound (derived from CIS historical sea ice coverage).

METHODS

Historical Sea Ice Data

Ship passage through the NWP was derived from the computer-based analysis of digitized Canadian Ice Service weekly and selected daily sea-ice charts at 4 km pixel resolution, which are freely-available on-line from 1968 to the present.

Sea Ice Regimes and Navigability

The criteria for successful ship transits is based on specified maximum partial ice concentrations by ice type, with high concentrations of multiyear ice combined with thick first year ice representing the limiting conditions to ship transits. Automated computer-based algorithms were developed to estimate the number of, if any, ship routes that would successfully allow transit of selected segments of the Northwest Passage Route using CIS digital ice data.

The Zone/Date System of Transport Canada, to regulate shipping in Canadian Arctic waters (Timco *et.al*. 2009), divides the Arctic into 16 zones, where the lowest number zone generally has the most severe ice conditions. This system is based on climatological means and does not reflect inter-annual variability or long-term trends. In 1996, Transport Canada switched to the more adaptable Arctic Ice Regime System (AIRSS), allowing for access decisions outside of the traditional Zone/Date System. The Arctic Ice Regime System of Transport Canada is a 4-part process that calculates an Ice Numeral (IN) from a class-dependent Ice Multipliers (IM) relating to ship capability.

The Ice Numeral is defined as;

$$IN = (C_a\, IM_a) + (C_b\, IM_b) + \ldots + (C_n\, IM_n) \qquad (1)$$

where C_a is the concentration in tenths of ice type a, and IM_a is the ice multiplier (IM) for ice type a. Open water is determined by subtracting 10/10ths concentration (i.e. 100% ice coverage) from the ice regime.

If IN ≥ 0 then passage is allowed, while for IN < 0 an alternative route must be found.

For decayed ice, the ice multiplier may be modified by increasing it by 1 and for ridged ice it should be decreased by 1. As the CIS digital egg code does not contain any information about decay or ridging, our analysis does not modify the ice multiplier for either case.

The International Association of Classification Societies (IACS) released in March 2008 a standardized global ice classification system for 7 polar class ships, but it has not yet been implemented by Transport Canada. There is an active community working on standardization of ice classification for vessels and ice multiplier tables. For our analysis, we used an IM Table (Table 1) modified from a system proposed by A. Kendrick (personal communication, 2010).

Table 1. Modified Ice Multipliers for Polar Class 4 vessels.

Thickness (m)		***0-0.1***	***0.1-0.3***	***0.3-0.7***	***0.7-1.2***	***>1.2***	***>2***
Ice Type		**Brash Ice** (New, Nilas)	**Young Ice** (Grey Ice & Grey White)	**Thin FYI** (1^{st} & 2^{nd} Stage)	**Med. FYI**	**Thick FYI**	**Old** (SY, MY)
Ship Type	***Egg Code***	1 or 2	3-5	7-9	1	6 or 4.	7. 8, 9
ICE MULTIPLIERS							
Polar 4		2	2	2	2	2	-2
CAC 4		2	2	2	2	1	-2.5

The IM values in Table 1 were applied to the CIS digitized sea ice data on a pixel-by-pixel basis to create IN maps; pixels were then grouped according to their IN values into five thematic classes:

1. **No Go** – Difficult (Red) ≡ IN ≤ -20
2. **No Go** – Less Severe (Orange) ≡ -20 < IN ≤ -10
3. **Transitional** (Yellow) ≡ -10 < IN ≤ 0
4. **Go** (Light Green) ≡ 0 < IN ≤ 20
5. **Open Water Conditions** (Dark Green) ≡ IN was flagged to 24

The resulting 'navigability maps' provide a detailed synopsis of sea-ice trends between 1968 to 2010. In order to better capture the large spatial and temporal variability, the study area was divided as outlined in Figure 4: the VMS was divided into 9 sections, and POWS into 2 sections.

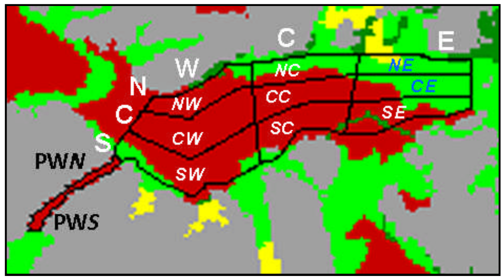


Figure 4. Division of Viscount Melville Sound into 9 sections, and Prince of Wales Strait into 2 sections.

Ship Transit Computations: Automated Path-finding

Automated algorithms were developed to detect safe routes through the deep-water VMS and POWS route as per AIRSS. Ice Numeral Charts were derived for PC4 and CAC 4 class ships using the Ice Multipliers provided above. A path-finding algorithm was run on individual charts to determine if a safe path existed.

Path finding algorithms have a long history in applications such as neural network route optimization and robotic control. Shortest path algorithms date back to the 1950's (Dijkstra, 2001). We have used a best-first search variant known as the, A* algorithm, which balances computational time with optimized path. The use of an estimated travel cost from the present position to the end-goal, approximates human based path finding.

Ice Navigability

The results for PC4 vessels for weeks 34 (mid-August) and 44 (late October) clearly show high-levels of accessibility into POWS and the northern and eastern areas of VMS; the southern sections (SW and SC) of VMS were consistently the least accessible due to the influx of MYI from the Beaufort Sea and Sverdrup Basin (Figure 5).

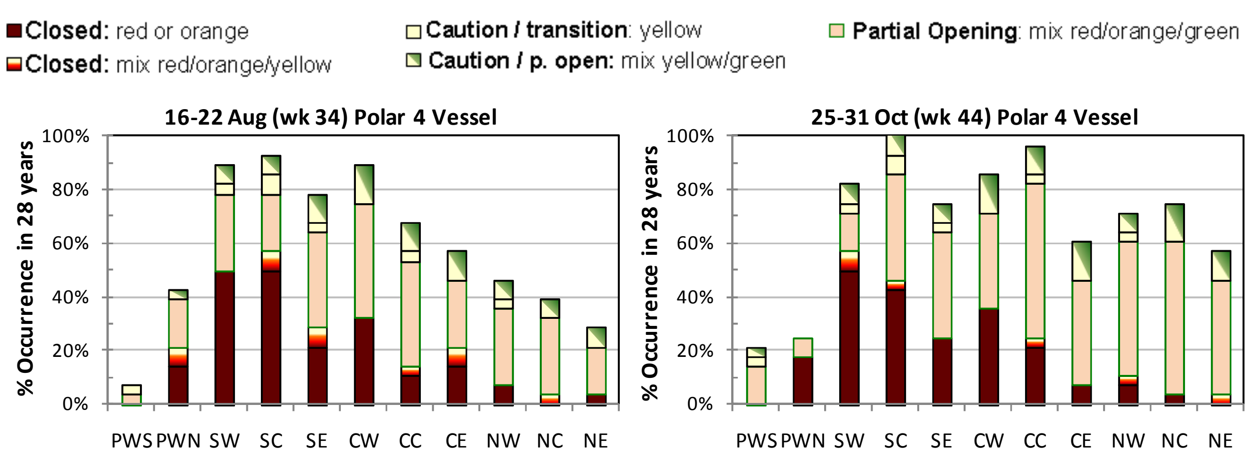


Figure 5. Climatological averages of percentage occurrences for the shipping conditions of Polar 4 vessels during weeks 34 (*left*) and 44 (*right*) in the 11 sections of POWS and VMS.

Year-to-year sea-ice variability and the increasing trend of MYI (Figure 2) are the most important determining factors on accessibility (Fissel *et al*., 2010). Figure 6 shows the access trends in the sections shown in Figure 3. The recent years of 2007-2009, which had historically low total sea-ice coverage for the Arctic, had only slightly better accessibility than conditions in the late 1990's. However, the years 1982 and 1983, but particularly 1999 and 2000 were significantly better.

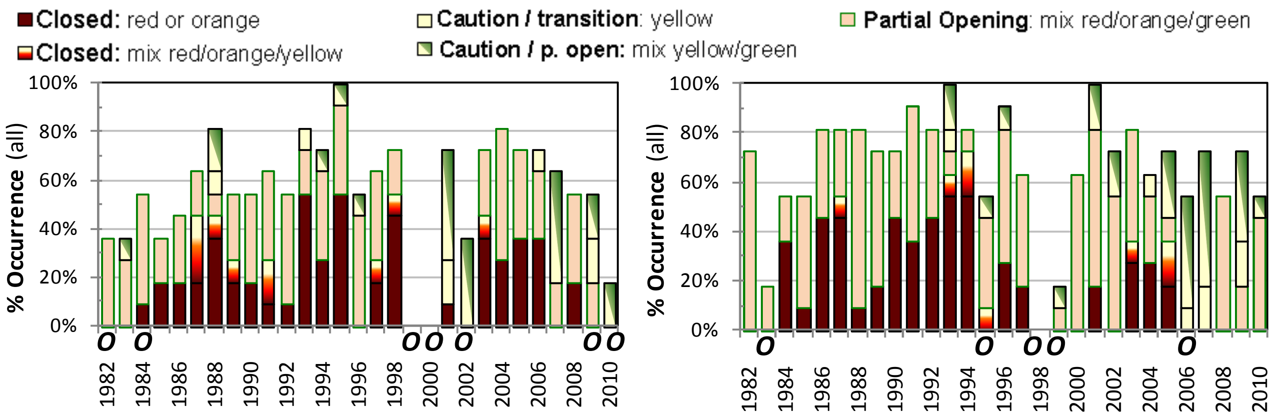


Figure 6. Percentage occurrences of closed or open conditions for Polar 4 vessels for the entire VMS/POWS area from 1982 to 2010 for weeks 34 (*left*) and 44 (*right*).

Automated Path-finding

We have run the A* path-finding algorithm with Ice Numeral charts derived for PC4 vessels. The center of POWS was taken as the start position for the searches and the end position was placed in the eastern part of VMS near Barrow Strait. This was run using all available weekly/monthly ice charts from 1982 to 2009.

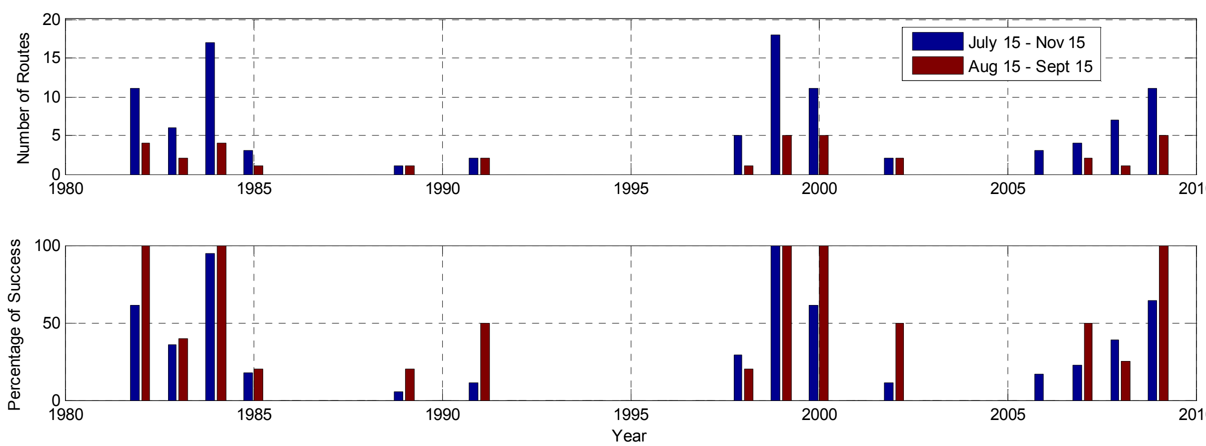


Figure 7. Number of automated safe routes found through POWS/VMS (upper graph) for the periods July 15-November 15 and August 15-September 15. Percentage of charts with safe routes for same time periods (bottom graph).

Successful routes were detected at various episodes in the record (Figure 7). The most recent episode, from 2006 to 2009, has a trend of increased number of successful routes found during the period of July 15 the November 15. This trend was not observed for the period of August 15 to September 15, which would generally be considered the preferred transit period. This most recent period did not have the greatest percentage of successful routes. The episodes in the early 80's and around 2000 had a greater percentage of successful routes.

Daily Ice Charts

The use of VMS for transiting between the eastern and western Canadian Arctic has been uncommon in the past several years. An analysis of Automated Vessel Observation System (AVOS) data available since 2003 provides records of only two passages both by the CCGS Amundsen (Figure 8) in October 2009 and October 2010.

CIS daily ice charts are available for times when CCGS Amundsen transited the NWP route. We have derived Ice Numeral Charts based on CAC4 Ice Multipliers provided above. The CAC4 classification has been previously used by Canadian Coast Guard to approximate the ice class of CCGS Amundsen (Canadian Coast Guard, *pers. comm.*).

Figure 8. CCGS Amundsen. Photo is courtesy of Canadian Coast Gaurd

Part of the 2010 route of the CCGS Amundsen through PWS and VMS is shown in Figure 9, with the Amundsen entering PWS on October 9 and leaving eastern VMS on October 12. The derived charts (Figure 9) indicate the extreme sensitivity of Ice Numerals to estimates of MYI concentrations. The 4/10 estimate of MYI for Oct 10, 2010 produced a positive IN while the 5/10 MYI of the following day makes a negative IN and conditions that should not have been safe according to AIRSS.

Ongoing investigations of the daily charts and additional comparisons with known transits through NWP will be used to further evaluate and improve the model.

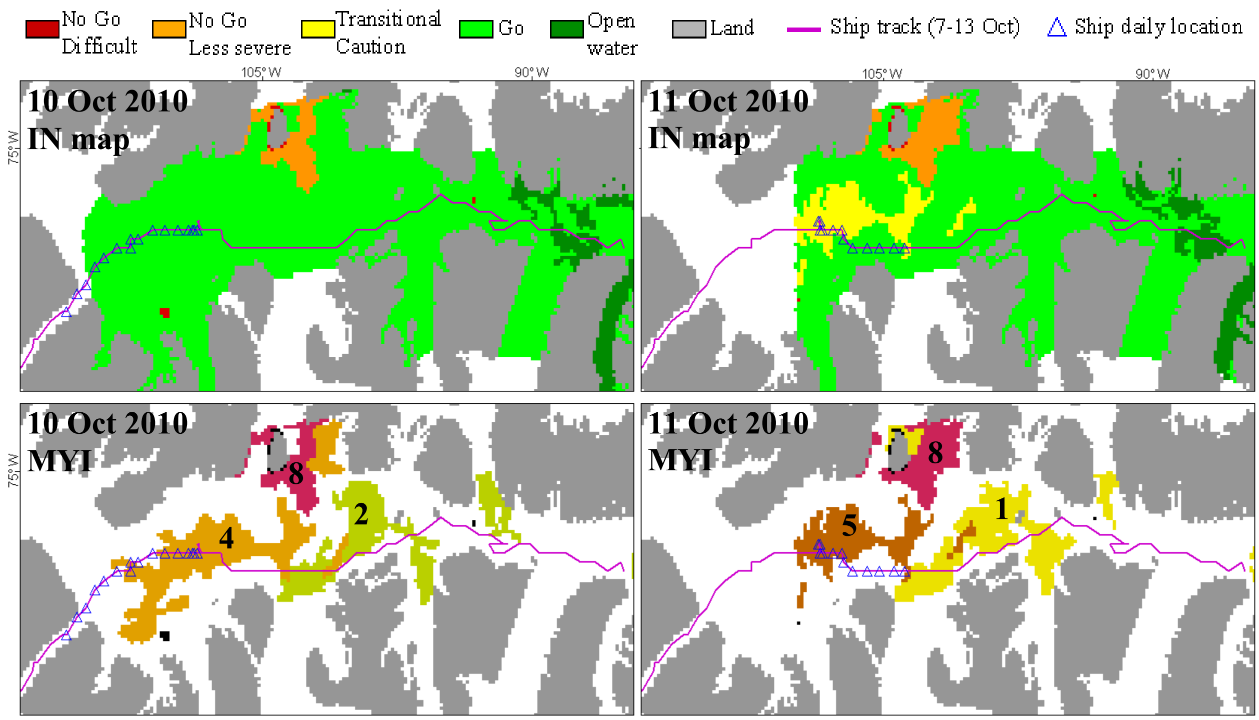


Figure 9. Daily IN navigation maps (top) for 10 October (left) and 11 October (right) 2010 for a CAC4 vessel, and matching Multiyear ice regimes (bottom) - numbers are concentrations in tenths. White areas indicate no data. Images are in Lat-Long, WGS84. Data derived from CIS daily ice charts for Parry Channel, and Sailwx data for the *Amundsen*.

CONCLUSIONS

Our results show a historically high degree of spatial and temporal variability of the ice regimes in the NWP, with an associated effect on shipping through the NWP. The long-term trends indicate a consistent blockage of the south section of the Viscount Melville Sound as a result of the predominant westerly winds.

Total summer ice coverage in VMS has been reducing at a rate about half that observed for the entire Arctic. More critical, MYI coverage has been increasing, as melting of FYI in the channels surrounding the Sverdrup Basin permits greater mobility of MYI through the Queen Elizabeth Islands. As long as MYI is present in the Sverdrup Basin, this trend could continue. More critical may be the large inter-annual variability of sea-ice, which makes passage more unpredictable.

The analysis of two passages of VMS by the CCGS Amundsen, in October 2009 and October 2010, underscores the importance of timely and accurate ice condition information in making passages through this chokepoint of the Northwest Passage. The results also indicate the sensitivity of the computed Ice Numerals to the concentrations of old ice, due to reported changes on a day to day basis in the CIS daily ice charts.

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